Exploring the Ocean Worlds

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***Abstract*—Including Earth, roughly a dozen water ocean worlds exist in the solar system: the relict worlds Ceres and Mars, large Jovian and Saturnian icy moons with vast interior oceans, and Kuiper Belt Objects like Triton, Charon, and Pluto whose geologies are dominated by water and ammonia. The ocean-world science puzzle – which may reveal whether life is widespread in the cosmos, why it exists where it does, and how it originates – can only be solved by exploring all of them. Potential life in these places could not have shared our origins, yet these worlds contain the only evidence about life that we can touch, essentially forever. Thus, their exploration has existential significance. Planning a multiworld exploration campaign would be a multi-generational undertaking. The technical challenges are diverse and formidable, far harder than at Mars: missions to the Jovian and Saturnian ocean worlds are severely power-limited; trip times can be more than a decade. And the science targets are global-scale oceans beneath kilometers of cryogenic ice. Today, we lack the instrumentation, subsystems, and machine-intelligence technologies needed. A systematic OWEP (ocean worlds exploration program) strategy can make most effective use of funding and time. The three priority ocean-world targets are Europa at Jupiter, and Enceladus and Titan at Saturn. Five hypothetical programmatic scenarios are compared to the default case. A coherent OWEP should have several parts: first, dedicated continuous investment in enabling technologies; and second, two directed-purpose, medium-class (~$1B) missions per decade that conduct pivotal investigations on a documented roadmap. A robust OWEP would cost about 1/40th more per year than NASA's current budget.**

Keywords—ocean worlds, astrobiology, icy moons, Europa, Enceladus, Titan

I. Introduction

Today we know of at least ten Ocean Worlds in our solar system, including Earth of course but otherwise a quite diverse set. To learn the limits of life in our solar system, we have to explore them all.

This will take many decades to do. Having a clear strategy is essential for prioritizing among the feasible options, and making the smartest investments.

Reference [1] discusses how to scientifically identify, confirm, and study worlds that may have, or may have had, oceans. Reference [2] surveys the phenomenology of ocean worlds throughout the solar system. Fig. 1 shows an ocean-world taxonomy and highlights the 'ocean-world starter set';

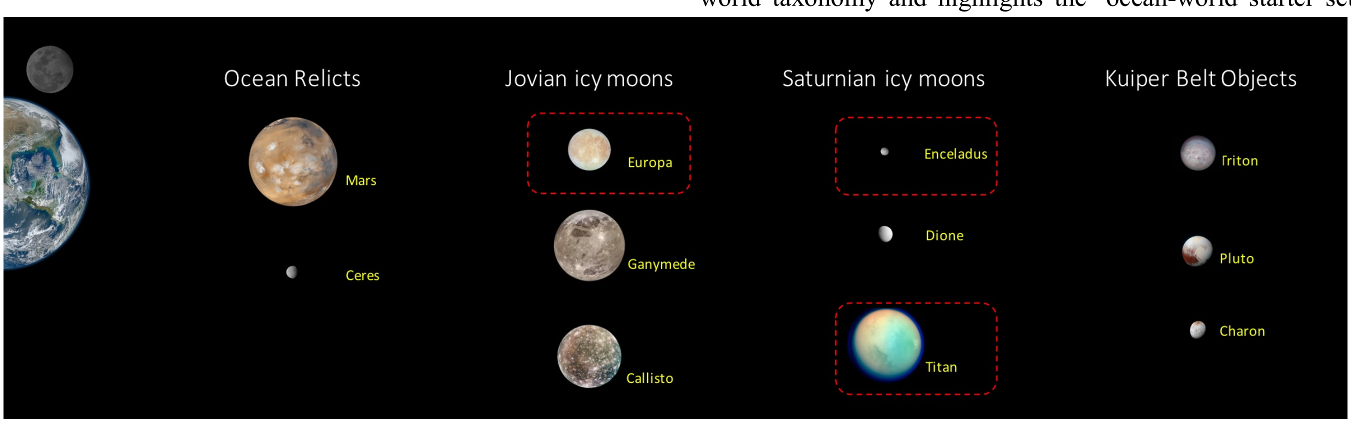

Fig. 1. **About a dozen ocean worlds** in the solar system offer the only tangible destinations where we can learn the limits of life in the universe. Three have special priority, for distinct reasons.

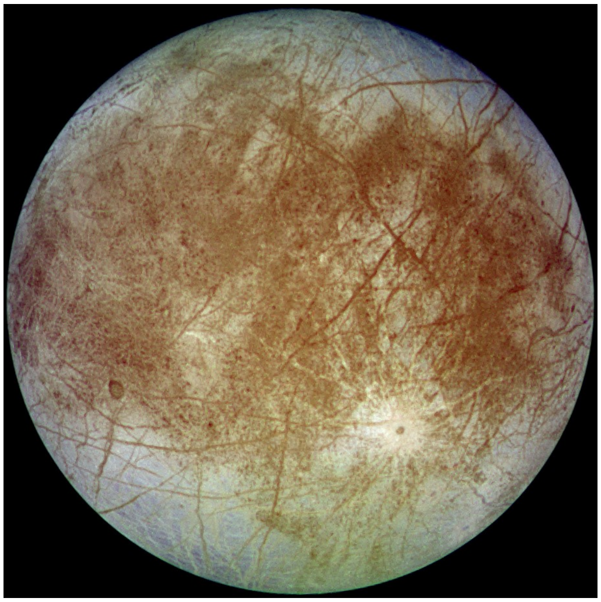

Fig. 2. **Europa** has one of the youngest surfaces in the solar system, an ice shell enclosing a salt-water ocean about twice as large as Earth's.

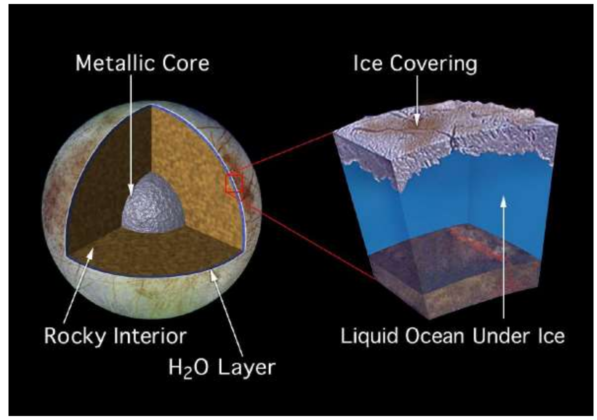

Fig. 3. **The floor of Europa's ocean is silicate rock**, and hydrothermal activity is likely.

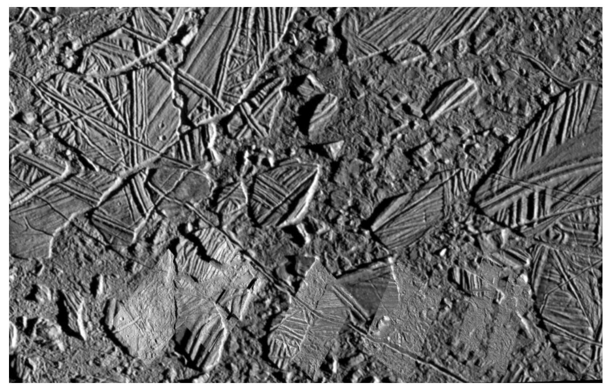

Fig. 4. **Significant exchange between Europan ocean and surface** is strongly implied by chaos morphology. Image: NASA/JPL/Univ AZ.

Europa, Enceladus, and Titan are the three most likely to reveal the most, soonest, about the extent and diversity of life in our solar system.

II. Europa

Europa, second-highest flagship mission priority of this decade [3] and the target of NASA's planned Europa Clipper, ought to be habitable (Fig. 2). Almost as big as Earth's Moon, it has an internal ocean with twice as much water as all of Earth's seas, and likely a hydrothermal seafloor (Fig. 3). The ice crust enclosing the ocean, of indeterminate thickness, is nonetheless geologically young, with ample evidence of dramatic tectonics that imply opportunities for exchange between ocean and surface over geologic time (Fig. 4). Io volcanos and Jupiter radiation provide a source of bio-essential elements and oxidants that get cycled into the ocean over geologic timescales.

Europa is our solar system's intrinsically most promising home for an alien ecology unrelated to Earth life. The next step of exploration, comprehensive investigation of the moon's habitability, is the purpose of Europa Clipper. Subsequent steps could include: 1) landing at a confirmed ocean-surface exchange zone, to access ocean material deposited near and on the surface; 2) local mobility to explore diverse material types and emplacements; 3) subsurface access, in pursuit of increasingly fresh material; 4) analysis of samples in terrestrial laboratories; 5) deep access through the ice shell into the ocean below, for in situ sampling and/or sample acquisition for return; 7) under-ice exploration of the ocean ceiling; 8) submarine exploration of the open ocean including potential seafloor hydrothermal sites.

Fig. 5 shows how all these steps cluster into three generations of exploration capability; Europa Clipper implements the first generation.

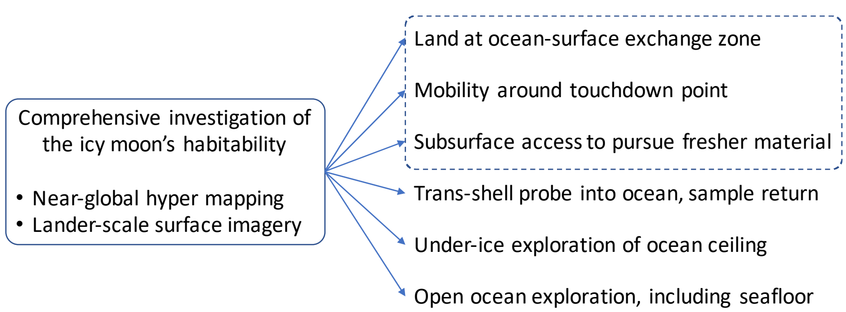

Fig. 5. **Europa program in three steps.** Europa ought to be habitable; but its large size and Jupiter's strong radiation make it a tough place to explore. Europa Clipper would build the foundation (solid box). First generation landers with today's technology could determine the ocean's chemistry, including possible biosignatures (dashed box). Open ocean exploration would require development of several new, mission-scale technologies.

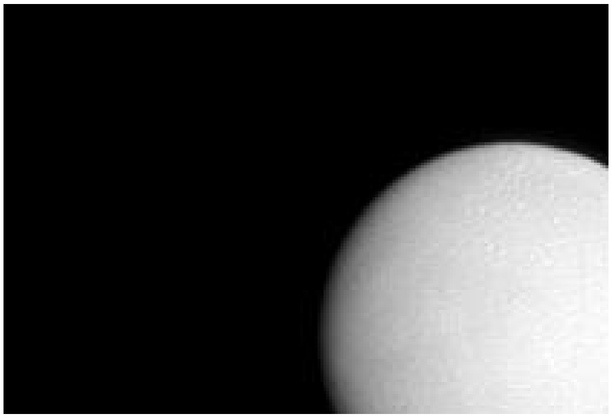

Fig. 6. **Enceladus spews material from its global ocean** out into space where it has been sampled directly. *Image: NASA/JPL/Space Science Institute*

Fig. 8. **Four tiger stripe fissures** bracket the South Pole. *Image: NASA/JPL/Space Science Institute*

III. ENCELADUS

Enceladus is known already to be habitable by today's definition (Fig. 6): global quantities of liquid water, salty, alkaline, long-lived; warm; with energy available from chemical gradients; organic chemistry (Fig. 7). Cassini made all these discoveries about the Enceladan ocean, most of them by first discovering that Enceladus is split at the south pole by four great fissures (Fig. 8). They are much warmer than the surrounding icy terrain [5], a fantastic landscape of shapes made of ice and snow (Fig. 9). Out of these fissures come about a hundred water vapor geysers [7] that loft dust grains and frozen ocean water droplets from the frothing liquid-vacuum interface in the conduits below. The droplet formation physics concentrates organics. The largest grains fall back to the surface to form the landscape, while others are carried by the vapor jets to form a vast plume extending far out into space, where they can be sampled directly with precise instruments. Cassini demonstrated how to do this.

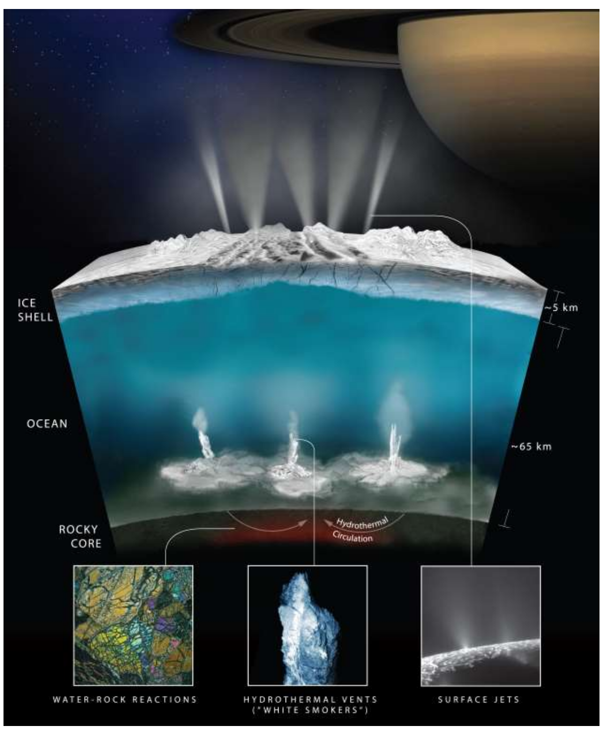

Fig. 7. **Enceladus is habitable** by today's definition, given multiple lines of evidence measured by Cassini.

Enceladus offers direct access to material known to originate in an environment known to be habitable. It is the easiest place to start directly searching for life elsewhere, via plume transects as flown by Cassini but with contemporary compositional analyzers. Subsequent steps could include: 1) soft capture of enough plume-grain material to apply developmental wet-chemistry and microscopy techniques; 2) collection, preservation, and return of samples for analysis in terrestrial laboratories; 3) accessing surface deposits adjacent to vents to collect large samples of the biggest grains for in situ analysis and/or sample return; 4) 'downhole' or drilled vent exploration to reach the liquid-vacuum interface; 5) under-ice exploration of the ocean ceiling; 6) submarine exploration of the open ocean, including the hydrothermal systems known to be there [4].

Fig. 10 shows how these steps cluster into three generations of mission type. The first and second groups appear amenable to medium-scale missions including New Frontiers, given instrument, payload, and sampling technology demonstrations.

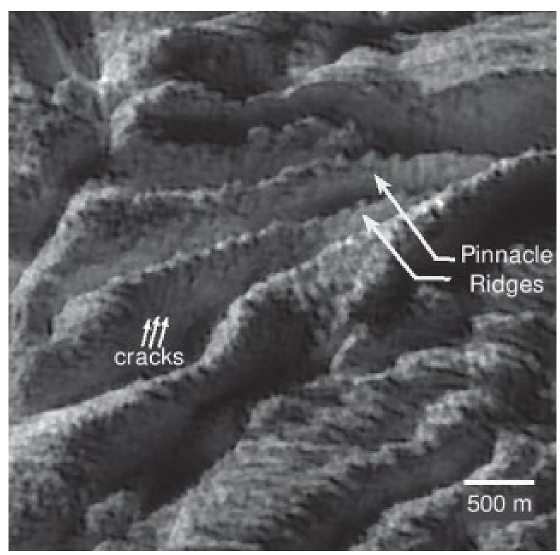

Fig. 9. **Highest resolution images of Enceladus** show complex, jagged surface in vent region. [6]

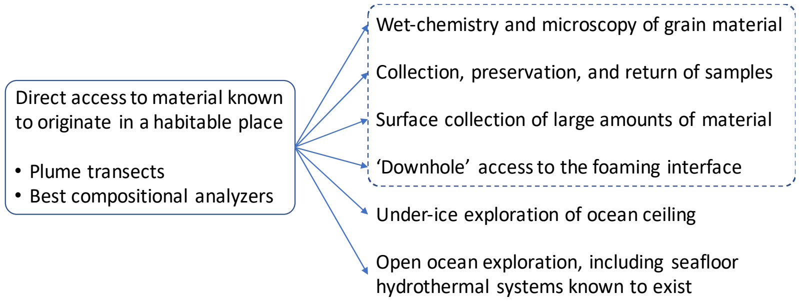

Fig. 10. **Enceladus program in three steps.** So far, Enceladus meets known definitions of habitability, and presents ocean material directly into space, providing a way to detect biosignatures outright (solid box). Advanced capabilities would allow comprehensive study of the ocean's organic contents up to microbial scale (dashed box). Remaining goals would require development of several mission-class technologies.

IV. Titan

Titan, half-again larger than Earth's Moon and the target of the Dragonfly concept in NASA's competitive New Frontiers program, is the solar system's 'organics factory' (Fig. 11). It too has a deep global water ocean, whose composition is unknown but whose bottom may be in contact with silicate rock (Fig. 12). The ice crust is thick, but atop and above it is a complex hydrocarbon world. The dense nitrogen atmosphere extends far into space. High up, sunlight just one percent as strong as at Earth is captured as chemical bonds by the formation of organic molecules, which grow into large haze particles that settle continuously onto the surface, forming the landscape along with the water ice, which is hard as rock at the temperature of liquid methane. Methane rain weathers this nitrogen-bearing organic sediment (Fig. 13), draining into large lakes and vast, deeply cold hydrocarbon seas. At suspected spots, cryovolcanic systems may warm the organic mix to liquid water temperatures for thousands of years; melt-pools from meteorites may last as long. At other suspected spots, subduction may even be dosing organics directly into the interior water ocean.

Titan is the best place to learn how different life forms might be from the water-based life we know. Its size, geomorphology, methanologic cycle, weather, climate, organics lifecycle including capture of solar energy, and 'two worlds' configuration make it one of the most complex solar system bodies to explore. Many missions of multiple types would be required to understand Titan as a planetary system, let alone its potential habitability and its state of organic evolution toward biology.

Fig. 11. **Titan is shrouded** in a thick nitrogen atmosphere that supports complex photo-organosynthesis. The surface can be imaged through 'windows' in the infrared. *Image: NASA/JPL/Univ AZ/Univ Idaho*

Cassini performed 127 targeted flybys in 13 years, which made the fundamental discoveries that prioritize it as an astrobiology target. These flybys broadly constrained the interior structure, imaged swaths of the surface in radar and infrared, observed weather, obtained a few bathymetry profiles, sampled atmospheric organics up to 100 u and detected hints of much more. The Huygens probe obtained stunning descent images of complex drainage networks and shoreline systems, an atmospheric structure profile, and cm-scale images of the surface at its landing site.

What is needed next is comprehensive reconnaissance of this extremely complex world: global tidal signature, gravity, and topography to determine how thick the ice shell is and whether the ocean is in contact with silicate rock at its base; global mapping at high enough resolution to characterize the global system cycles; a detailed inventory of the stratospheric organics factory to reveal what is being made and how; and analysis of the chemical fate and astrobiological state of weathered organics on the surface, particularly in areas where contact between organics and water may have occurred. Subsequent steps could include: 1) aerial exploration beneath the thick haze; 2) buoyant exploration of hydrocarbon seas;

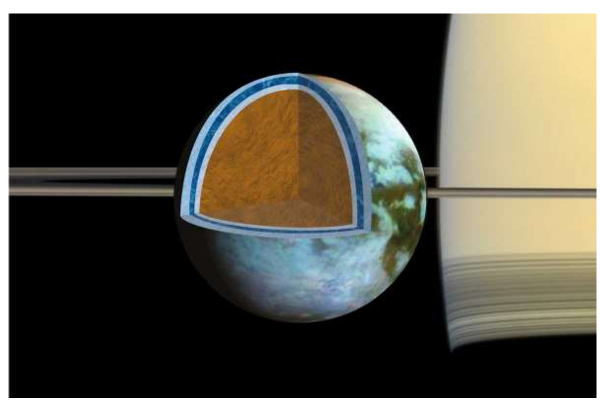

Fig. 12. **Titan also has a global water ocean enclosed** within a thick ice shell; the seafloor may be in contact with silicate rock. (Proportions correct for hydrated silicate core.)

Fig. 13. **Global-scale methanological cycle** erodes Titan's organic sediments, draining the weathered by-products into lakes and seas. *Image: René Pascal/ ESA/NASA/JPL/University of Arizona*

3) mobile surface exploration of geologically and astrobiologically promising locales; and eventually, 4) return of samples for analysis in terrestrial laboratories and 5) access into the interior ocean through the cryogenic ice crust.

Fig. 14 shows how these steps cluster into three generations of mission capability, each encompassing several missions' worth of exploration projects. New Frontiers could take the first step and much of the second; a mission selected in 2019 could by 2035 start opening this cold, alien world to informed exploration by subsequent in situ investigations.

Taken together, the three primary ocean worlds give us places to search for extant life, complex life, pre-life, and even weird life. Thus they constitute the core mission agenda for empirical astrobiology. While pursuing all three stages of exploration at each world would take more than a century's worth of advanced technology development and deep-space missions, the first 'next steps' could be accomplished at all of them in the 2030s, in a carefully structured program.

V. Ocean World Exploration Program Today

The US Congress directs NASA to implement a "virtual" Ocean Worlds Exploration Program using a mix of mission classes and types [8]. The next strategic milestone will be the emergence in 2022 of US planetary Decadal Survey priorities that succeed the current Decadal Survey Vision & Voyages [3].

In the meantime, several actions to explore ocean worlds are using existing program means. NASA is developing the Europa Clipper multi-flyby habitability reconnaissance mission in time for a 2022 launch [9]. NASA is also studying concepts for a second large mission, a Europa Lander that would literally scratch the surface for biosignatures at a site to be identified by Europa Clipper [10]. For the most aggressive schedule, a second SLS launch would be needed, and instrument selection would need to occur in 2018 [11].

ESA is developing the large-class mission JUICE (Jupiter Icy Moons Explorer) that will enter orbit around Ganymede by 2032 [12]. High-capability instruments applicable to ocean worlds are developed across Europe, funded by the respective national agencies.

NASA also solicits PI-led mission proposals. The agency added an Ocean Worlds Theme to the Decadal-specified list of five candidate science objectives for the New Frontiers program, NASA's billion-dollar class competitive mission opportunity. One Titan concept (Dragonfly, a mobile lander to conduct in situ analysis of surface organics) is currently in Phase A; mission selection for a launch by 2025 is scheduled for mid-2019 [13]. The subsequent New Frontiers competition may or may not occur before the next Decadal Survey sets priorities.

The smaller (roughly half-billion-dollar), but more frequent Discovery mission opportunities are challenged to provide worthy value propositions for exploring ocean worlds; three concepts have been declined since 2010, and the next competition is in 2019 for launch in 2026. Finally, advancements funded by proposing institutions and by NASA MatISSE and COLDTech [14] instrument and technology awards will inform mission concept studies commissioned by NASA in 2019 to support the community Decadal Survey process.

VI. Ocean World Program Stakeholders

The activities described above comprise today's 'virtual' OWEP (ocean worlds exploration program). As a strategy, a virtual OWEP has limited effectiveness due to sparse opportunity cadence and the stochastic nature of PI-led priorities. It does offer the programmatic advantage of maintaining status quo processes, and it exercises competitively sharpened science and formulation constituencies.

But this community now has the potential and capacity to prosecute a richer, more organized and orderly program, given that an implementing community is building around the Europa Clipper project and Europa Lander Pre-Project. If an important strategy criterion were 'the fastest way to learn the limits of

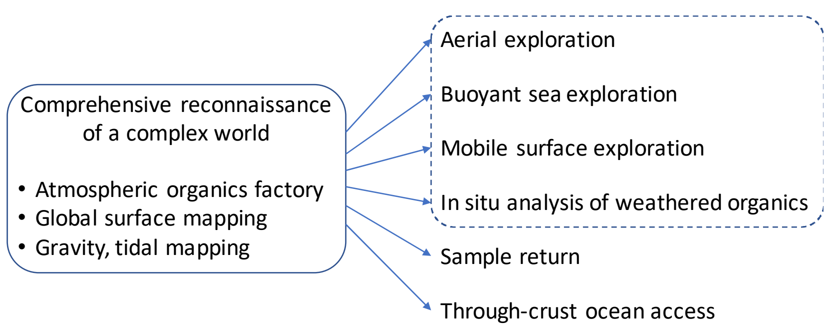

Fig. 14. Titan program in three steps. Apart from Earth, Titan is one of the most complex worlds in the solar system, easily proffering a century's worth of exploration missions. Next we could directly sample its organics and map its globe inside and out (solid box). This would reveal how best to conduct in situ investigation using advanced technologies (dashed box). Several major mission-class technologies would be required for the remaining goals.

life,' then faster options are available; some of these would require the virtual program to become a real one. Line-item programs gain a coherence in the minds of sponsors and participants alike that could focus and unleash the talent already organized. This could vault exploration of the ocean worlds forward.

An exemplar for the utility of a structured program is the Mars Exploration Program (MEP). In only 15 years, the MEP made diverse, deep scientific and exploratory leaps at Mars, culminating in proof that the planet once did have long-acting, clement liquid water. This remarkable record demonstrates how sustained investment within a structured program can assure at once a robust science community, healthy technical workforce, and stepwise progress on a consensus strategic roadmap. The MEP has extended human action and knowledge out to a frontier keenly relevant to how we see ourselves in the cosmos. The quest to know if life ever existed on Mars is now convolved with societal anticipation of a human future there, a milestone that could happen in this century.

But the scientific context has changed. Discoveries elsewhere have revealed that Mars and Ceres are end-members of a family: paleo-relict ocean worlds [15]. How long do ocean worlds last? How far do they progress toward life? Perhaps even, how does life adapt as habitable conditions fade?

In the case of the more distant ocean worlds, containing large extant oceans, only humankind's avatars can gain access: Jupiter imposes a hazardous radiation environment at the Europan surface; Saturn is a half-decade away even with heavy-lift launch. Through sophisticated telepresence and future in situ instruments, we could learn how habitable conditions may arise, vary, and be sustained, and how far they may have progressed toward complexity and life. 'Following the water into the ocean worlds' is the best way to learn whether another part of our universe is also alive.

VII. Lessons from the Mars Exploration Program for Ocean Worlds Exploration

The strategy analysis summarized here demonstrates that a virtual OWEP cannot match the focus, velocity, or persistence of a structured program like the MEP. In particular, only a 'middle class' of directed-purpose missions could guarantee a steady, orderly cadence of key results, which in turn would provide a foundation for strategic, flagship missions to implement complex, empirical planetary science.

Yet the MEP is not a directly applicable template: six enabling conditions cannot be ported directly over to an OWEP that tackles the three highest-priority ocean worlds; the lessons must be adapted to be constructive. The first two are imposed by nature.

1) Mars-class missions are technically moderate in many dimensions.

After the Moon and Venus, Mars is our nearest planetary neighbor, at the outer edge of our sun's 'habitable zone'. One-way light-time from Earth ranges from 3–20 minutes; sunlight is 44% as strong as at Earth, and the Mars night lasts nearly the same as Earth's (the diurnal period is 24h 39m 35s). Surface temperatures range between 130–308 K. The CO_2 atmosphere is dense enough to use for entry and descent deceleration, albeit thin enough that a succession of technologies is needed to reach zero velocity at the surface; landing at the higher altitudes in the southern highlands has not been demonstrated. The surface can be explored from orbit in all wavelengths.

Sunlight at Jupiter and Saturn is, respectively, only 3.7% and 1% as strong as at Earth. Solar power is feasible for orbiters, as demonstrated by Juno. Landers for the icy moons are harder to design for solar power: the Europa and Enceladus days last 3.55 and 1.37 Earth-days, respectively. Titan's day lasts almost 16 Earth-days, and its hazy atmosphere absorbs 90% of the feeble sunlight anyway, so extended surface operations would require radioisotope power.

Titan has the most benign atmosphere in the solar system for entry, descent, and atmospheric flight: dense nitrogen. However, Europa and Enceladus are airless, so propulsive descent is required; Enceladus is quite small, with only about 1/87 g at the surface. By contrast, landing on Europa is like landing on Earth's Moon; it has about 1/7 g; in addition, it orbits inside Jupiter's strong radiation belt, receiving about 540 rem/day.

Much Mars science is accessible on the surface. However, a strong consensus holds that any prospect of finding extant life requires getting deep: into aquifers, paleo-volcanic areas including lava tubes, or down boreholes. However, this desiccated ocean world has given humanity a tremendous adventure already, via exposed rocks that may contain paleoindicators of life.

By contrast, the Jovian and Saturnian ocean worlds are icy moons: their liquid oceans lie beneath kilometers-thick ice crusts. Our natural exploratory urge is to gain access to the potential habitats inside, as rapidly as possible. Yet it is also likely that these moons' surfaces can give us rich exploration adventures along that quest, akin to those at Mars, earlier and more simply than ocean-access missions. Operations complications hidden by thick ice are not the only challenge: on their surfaces, the Jovian and Saturnian icy moons are not just icy, they are cryogenic. Europa ranges from 50–110 K; Enceladus ranges from 33–145 K; Titan is about 94 K. Such cold conditions, in which ice is as hard as concrete, challenge the performance of aerospace components with heritage.

Titan's atmosphere and surface, and Enceladus' surface, are all likely accessible within New Frontiers resources. The largest uncertainty for Enceladus is surface mechanics in the dramatic landscape near the vent openings. We also lack imagery at the scale of a lander, so next-step missions must be designed to handle a wide range of possible conditions. At Europa, large gravity and Jovian radiation make landing and functioning on the surface quite challenging. But here we expect a tectonically controlled landscape, with ocean material embedded in the cryogenic ice.

Not one of the three primary ocean worlds can be reached or explored as easily as Mars. This gap poses a significant, inescapable contrast between the MEP and any OWEP. Some of the challenges, like cryogenic operations and modular radioisotope power systems, are common to all icy moons, and are therefore amenable to cross-program technology investment.

2) 26-month synodic period, and half-year transfers, allow Mars exploration to respond to new knowledge with new missions on a half-decade cadence.

Ballistic transfer takes less than once around the sun, and a Hohmann transfer window occurs at just over two-year intervals. This fact of celestial mechanics allows mission development – based directly on fresh technical experience and emergent science – with half-decadal periodicity.

Reaching the giant-planet ocean worlds is harder and takes longer, and therefore costs more on average. Standard expendable launch vehicles impose half-decade (to Jupiter) or decade-long (to Saturn) transfers due to multiple gravity assists in the inner solar system, which in turn drive the hot limit for flight components. (The fastest chemical propulsion trajectories to Saturn take seven years, given a Jupiter gravity-assist that is available only every 18 years.) Very large rockets in development today could halve these trip times and avoid the complications of flying an icy-moon spacecraft inward around the sun first; so too would a high-power SEP (solar electric propulsion) stage such as those available from today's private sector.

3) Extra-project investments can assure development of enabling technologies that are key to strategic progress.

A mission series allows systematic investments in key technologies to be amortized over several missions, without fully burdening any project or subsuming the technologies' requirements to singular mission goals. The MEP tried to maintain such an MTP (Mars Technology Program) as a dedicated program budget line item, but strategic technology budgets and early infusion are notoriously difficult to protect and assure, given the focus on tactical requirements that all projects develop. Nonetheless, key capabilities developed by MTP and its successor investments, such as software-defined radios, EDL (entry, descent, and landing), rocker-bogey roving, and radioisotope power generators that operate in the Mars atmosphere, have been essential to MEP success.

Without a sustained technology program, a virtual OWEP would lack the ability to make multi-year investments in strategic core technologies. COLDTech is the virtual OWEP's seed of an OWTP (ocean worlds technology program); in its first year COLDTech distributed about \$25M across 16 competitively awarded, two-year maturation initiatives [14]. This first round of small investments is quite diverse: some could be used at multiple worlds, some are singular, and some are aimed at missions far along any reasonable roadmap. Achieving project-ready TRL for any of them would require increased funding, necessitating COLDTech growing significantly, down-focusing its portfolio, or both. Such decisions require a top-down strategy difficult to reconcile with today's competitive mission-objective selection process.

A strategic OWTP could establish metrics-driven capability advancements needed for all three primary ocean worlds: 1) autonomous exploration that can conduct branched, open-ended science investigations despite hours-long communication delay with Earth, or in conditions where Earth control is not possible at all; 2) planetary protection of potential habitats, and of Earth from returned ocean-world material; 3) integrated protocols for making life-detection inferences, including measurement techniques not yet flown in deep space; 4) acquisition, handling, and preservation of astrobiological samples in forms ranging from rock-hard ice to clathrates to liquid water to volatiles; 5) mechanisms and electronics that survive cryogenic conditions and avoid thawing native material; 6) modular radioisotope power systems for landed and submerged mission operations in potential habitats.

Such strategic investment could systematically mitigate the intrinsic challenges of exploring ocean worlds described in the previous section; without this, each first mission would have to absorb – and then be prey to the parallel schedules and cost uncertainties of – maturation of its core enabling capabilities.

4) Ongoing operational infrastructure 'lowers the bar' for individual missions.

A top program priority throughout MEP history has been sustaining telecom relay assets in orbit. Mission-critical events like MOI (orbit capture) and EDL are covered fully, providing technical confidence for each next mission in the program. The assets' orbits are routinely shifted to assure best coverage.

The Mars assets do more than link data nodes. Each also carries a sophisticated science instrument payload. The whole surface has been mapped in infrared (mineralogy), thermal emission (dust, soil, rock, ice), and visible (morphology) wavelengths. About 1/40 of the surface is imaged at half-meter pixel scale. Altogether, and deeply enhanced by human-scale scenes provided by roving surface avatars, this comprehensive exploration of the planet has made it feel familiar.

An OWEP multi-world exploration objective would require a different type of infrastructure, because the highest scientific priority would take next steps at each of the three primary ocean worlds. Trip time tops the list, based on celestial mechanics. Thus the first most-enabling OWEP common infrastructure would be high-performance propulsion into the giant-planet systems.

For example, with a solid-rocket-motor kick stage, SLS could deliver roughly 2000 kg into Saturn orbit only four years after launch. Combining a conventional launch vehicle (e.g., Atlas V) with a 25 kW SEP in-space stage could deliver it with a 5–6 year flight time. Such heavy-lift launch and SEP-stage opportunities occur every year. The Falcon Heavy and commercial SEP spacecraft are already demonstrated.

5) The agency determines MEP project new-starts within a single program budget line.

This administrative structure allows the agency to manage a portfolio of related projects to get the most value from public money while making strategic progress. Congress can and does provide direction about individual projects, but dividing the budget into multi-project programs gives the agency tactical maneuvering room.

For planetary science, NASA has multiple programs: MEP; ExoPlanet Exploration (in the Astrophysics Division); the competed mission opportunities New Frontiers, Discovery, and SALMON; and a large portfolio of research, instrument

TABLE I. MARS EXPLORATION PROGRAM IN FOUR PARTS. SCIENTIFIC INFRASTRUCTURE MISSIONS (GRAY) AND LESSONS FROM EARLY FAILURES (ORANGE) ESTABLISHED THE FOUNDATION FOR CHALLENGING IN SITU EXPLORATION (GREEN) AND THE CONTEXT FOR COST-CONSTRAINED, COMPETITIVELY SELECTED MISSIONS (TAN).

Project	Launch	Rough Cost[a] ($B FY17)
Mars Observer	1992	1.14 [16]
Mars Pathfinder (Discovery)	1996	0.48 [17]
Mars Global Surveyor	1996	0.34 [18]
Mars Climate Orbiter	1998	0.35 [19]
Mars Polar Lander	1999	
Mars Odyssey	2001	0.59 [20]
Spirit and Opportunity, MER Rovers A & B	2003	1.13 [21]
Mars Reconnaissance Orbiter	2005	0.77 [22]
Phoenix (Scout)	2007	0.56 [23]
Curiosity (MSL)	2011	2.43 [24]
MAVEN (Scout)	2013	0.56 [25]
InSight	future	0.63 [26]
Subtotal as of 2017		***~ $9B FY17***
Mars 2020 rover	future	future
"NeMO" Next Mars Orbiter	potential	future

a. Variable assumptions (see references); use only for rough sense of scale.

maturation, and technology development programs. A line-item OWEP, supported by an OWTP, would allow the agency to guarantee a predictable rate of progress on the quest to understand life, exactly as MEP and MTP has done.

Because such a line-item program entails a shift of programmatic "degrees of freedom" from general to focused – such a move would require significant stakeholder commitment. Today, all planetary missions outside the Mars mainstream and smaller than flagship-class are selected in three competitive programs (SALMON, Discovery, New Frontiers).

Priorities across all of planetary science are set by the Decadal Survey, a complex community engagement process. The next survey, culminating in 2022, will consider discoveries at Enceladus and Titan made since 2010, when the current survey was done; the evolving state of knowledge from hundreds of related research papers published in the meantime; capability-driven mission concepts developed by NASA from FY16 through FY20; and planning analyses. It will issue the authoritative assessment of the state of knowledge of planetary science in 2022, predictions about what might be feasible within the 2023–2032 decade, and guidance for how NASA should allocate science objectives for that decade among the opportunity classes. A prioritized list of strategic missions and a non-prioritized list of New Frontiers objectives is expected.

6) Directed missions in the $0.5–1B class constitute the MEP's essential connective tissue between flagship missions.

Table 1 lists the US Mars mission projects since Viking[1]. Punctuated by flagship peaks, a cadence of small-to-large missions has propelled the rapid scientific exploration of Mars. Most of these were directed missions: NASA chose sets of functions and measurements that would steadily advance the front of scientific knowledge, while laying in infrastructure, demonstrating capability, and learning facts that helped the flagship missions be designed and succeed. The rate of startling discoveries at Mars is proof that such a strategically defined program can be a potent tool for progress.

The MEP foundational missions cost $0.25–1.1B in today's money and were developed to exploit launch opportunities occurring every 26 months. Eight of them were launched in the 13 years from 1992 to 2005. They supported the MER twin rovers, the flagship Curiosity geochemistry rover, and are expected to support the flagship Mars 2020 rover. They enabled the competitively selected science missions Phoenix, MAVEN, and InSight to enrich and broaden the 'Follow the Water' strategic thrust at the core of the MEP.

Equivalent strategic authority to direct a line-item OWEP would likely require creating a class of directed-purpose missions whose resources (~$1B) could be commensurate with ocean-world challenges. Their implementation could be competitively awarded; strategic progress requires only that their purpose be directed.

VIII. PLANNING AN OWEP

NASA could consider options spanning incrementally from today's virtual OWEP to a formally planned OWEP that adopts lessons from the successful MEP. Each step of this scale would pose programmatic challenges, but also yield commensurate benefits of efficiency and velocity.

Case 0 is the default state: Europa Clipper flagship mission, with results starting in the mid-2020s; potential Europa Lander flagship mission, with results as early as ~2030. Those results would inform next steps.

Case 1 would be a 2019 selection of Dragonfly in 2019, with results starting in 2035–36; and/or a different concept selected in NF5 in 2024, with results ~2040. The earliest results would emerge later than the entire span of the next Decadal Survey, to be published in 2022. The vision and priorities of PIs and science teams, if they win, would define OWEP direction.

Case 2 would expand the New Frontiers program, selecting two missions per opportunity. The Announcement of Opportunity could be defined to favor an OW mission award in each competitive round. This option would double the capacity of the program, allowing it simultaneously to implement science across the solar system while making steady progress exploring the ocean worlds. Key questions about all three primary ocean worlds might be answered by mid-century. Is Europa habitable? Where and how can we gain access to ocean material? Is the Enceladan ocean chemistry conducive to life? Do the surface deposits contain evidence of life? Does the organic photosynthesis in Titan's upper atmosphere incorporate oxygen? Do Titan's evolved organics ever come into contact with water?

This option, launching two ocean worlds missions per decade, would cost roughly $200M per year more than today's program [27]. It would sustain a technical community capable of developing ocean-world missions, and a science community expert in interpreting results. However, the science priorities

1 All costs discussed in this paper are in $FY17, except as noted.

would be defined by individual PIs and their teams rather than by a community-consensus roadmap.

Case 3 would create a $1B directed-purpose mission class. Prior mission competitions indicate that significant investigations can be done at the billion-dollar level. If able to direct a strategic sequence of such missions, combining pivotal science objectives and technology demonstrations, NASA could propel the ocean-worlds quest for life with velocity and effectiveness comparable to what MEP has achieved at Mars.

Scientific and technological progress would follow the priorities of a documented strategic roadmap. As with the MEP, competitively selected PI-led New Frontiers missions might occasionally augment the core program.

This option might cost as little as Case 2 (i.e., an extra ~$200M/yr). But it could cost up to roughly twice that much if multiple directed-purpose objectives get aggregated into small-flagship-class missions.

Case 4 would add a strategically managed ocean worlds technology program. This penultimate step would give NASA budgetary and planning flexibility to invest in capabilities that are useful for multiple missions, maturing them at the right time to 'turn on' key nodes of an integrated roadmap. Without this, progress would be prey to the stochastic selection environment of undirected programs like COLDTech, PICASSO, and MatISSE, where selections are constrained by investigator interests, proposal quality, and evaluator assumptions, rather than NASA strategy.

Sequestering technology program resources would be tough to sustain; they historically end up being folded under project control, which reduces the diversity and infusion rate of advanced capabilities. Despite the daunting inherent physical differences between exploration of Mars and of the primary ocean worlds, this option would equip NASA to pursue the most promising leads, in the most appropriate sequence, using the most applicable technologies, on its quest.

Using the MEP history as a guide, a robust OWTP program might be protected at about 10% over the OWEP budget, thus perhaps ~$50M per year in addition to the mission commitment of Case 3. Thus the budget enhancement for a robust OWEP would total about $500M/yr.

Case 5 would establish a formal OWEP. This structural administrative step would not be cosmetic: it would put the reins of foundational missions, technology campaigns, championship of and responsibility for ocean-worlds flagship missions, sponsorship of competitive ocean-worlds missions and projects, and NASA OWEP brand management in the hands of an agency leader.

A program office with operations staff could efficiently administer the built-up components and coordinate interfaces with partner organizations inside and outside the agency. It would advocate for the ocean-worlds scientific frameworks and priorities in agency planning and definition of research categories that affect many stakeholder communities – including geophysics, geochemistry, astrobiology, oceanography, organic chemistry, and other domains of space and life science; and mission, system, spacecraft, instrument, and laboratory providers. It would maintain planning roadmaps for missions and technologies, to keep stakeholder alignment visible. It would synthesize emergent results with plans and decision points, and coordinate outreach messaging, representing to the wider world NASA's quest to find and understand life in the universe.

IX. Time – Opportunity and Threat

A structured OWEP would be scientifically complex and technically challenging, spanning many missions and decades. While this allows advanced capabilities to be developed, it also frustrates the career objectives of any given investigator. Shortening trip time would increase the mission-to-mission pace; two enablers are heavy-lift launch and deep-space electric propulsion. But even with such improvements, mission new-start opportunities are rare, and result slide to the right as those decisions come and go. Without transcending Case 0 (the status quo), NASA lacks maneuvering room to accelerate its quest for life.

X. Conclusions

Many NASA missions – those of the MEP, plus Voyager, Galileo, Cassini, Dawn, and New Horizons – have identified a class of worlds not envisioned just a few decades ago: worlds with large extant or former liquid water oceans.

Of these, Europa, Enceladus, and Titan are very different but have the best combinations of attributes to motivate a significant and achievable human quest: to tangibly learn the limits of life in places we can reach with 21st-century technology.

In this our century, we could find out whether we are alone in the cosmos. Next steps toward exploring the primary ocean worlds are either already underway (e.g., Europa Clipper), under study (i.e., Europa Lander), or awaiting potential selection in the competitive New Frontiers mission program (i.e., Dragonfly).

Beyond these first steps though, the strategy challenge for an OWEP is how to implement and sustain a series of ambitious steps within plausible budgetary scenarios on timescales meaningful to practicing scientists, lawmakers, and the public – while also preserving balanced solar system exploration. Significant progress could be guaranteed for about $0.5B per year, an increase of only 1/40th of the NASA budget. The payoff would be an unprecedented achievement of science and the humanities: knowledge of whether we are alone in our solar system.

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The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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